

# ICARUS detector and refurbishing plans

A. Fava

Padova University and INFN

on behalf of

ICARUS Collaboration

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# ICARUS-WA104 Collaboration

M. Antonello<sup>8</sup>, B. Baibussinov<sup>4</sup>, V. Bellini<sup>2</sup>, P. Benetti<sup>3</sup>, S. Bertolucci<sup>1</sup>, H. Bilokon<sup>7</sup>, F. Boffelli<sup>3</sup>, M. Bonesini<sup>9</sup>, J. Bremer<sup>1</sup>, E. Calligarich<sup>3</sup>, S. Centro<sup>4</sup>, A.G. Cocco<sup>11</sup>, A. Dermenev<sup>12</sup>, A. Falcone<sup>3</sup>, C. Farnese<sup>4</sup>, A. Fava<sup>4</sup>, A. Ferrari<sup>1</sup>, D. Gibin<sup>4</sup>, S. Gninenko<sup>12</sup>, N. Golubev<sup>12</sup>, A. Guglielmi<sup>4</sup>, A. Ivashkin<sup>12</sup>, M. Kirsanov<sup>12</sup>, J. Kisiel<sup>14</sup>, U. Kose<sup>1</sup>, F. Mammoliti<sup>2</sup>, G. Mannocchi<sup>7</sup>, A. Menegolli<sup>3</sup>, G. Meng<sup>4</sup>, D. Mladenov<sup>1</sup>, C. Montanari<sup>3</sup>, M. Nessi<sup>1</sup>, M. Nicoletto<sup>4</sup>, F. Noto<sup>1</sup>, P. Picchi<sup>7</sup>, F. Pietropaolo<sup>4</sup>, P. Płoński<sup>13</sup>, R. Potenza<sup>2</sup>, A. Rappoldi<sup>3</sup>, G. L. Raselli<sup>3</sup>, M. Rossella<sup>3</sup>, C. Rubbia<sup>\*,1,5,8</sup>, P. Sala<sup>10</sup>, A. Scaramelli<sup>10</sup>, J. Sobczyk<sup>15</sup>, M. Spanu<sup>3</sup>, D. Stefan<sup>10</sup>, R. Sulej<sup>16</sup>, C.M. Sutura<sup>2</sup>, M. Torti<sup>3</sup>, F. Tortorici<sup>2</sup>, F. Varanini<sup>4</sup>, S. Ventura<sup>4</sup>, C. Vignoli<sup>8</sup>, T. Wachala<sup>6</sup>, and A. Zani<sup>3</sup>

<sup>1</sup>CERN, Geneva, Switzerland

<sup>2</sup>Department of Physics, Catania University and INFN, Catania, Italy

<sup>3</sup>Department of Physics, Pavia University and INFN, Pavia, Italy

<sup>4</sup>Department of Physics and Astronomy, Padova University and INFN, Padova, Italy

<sup>5</sup>GSSI, Gran Sasso Science Institute, L'Aquila, Italy

<sup>6</sup>Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Science, Kraków, Poland

<sup>7</sup>INFN LNF, Frascati (Roma), Italy

<sup>8</sup>INFN LNGS, Assergi (AQ), Italy

<sup>9</sup>INFN Milano Bicocca, Milano, Italy

<sup>10</sup>INFN Milano, Milano, Italy

<sup>11</sup>INFN Napoli, Napoli, Italy

<sup>12</sup>Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia

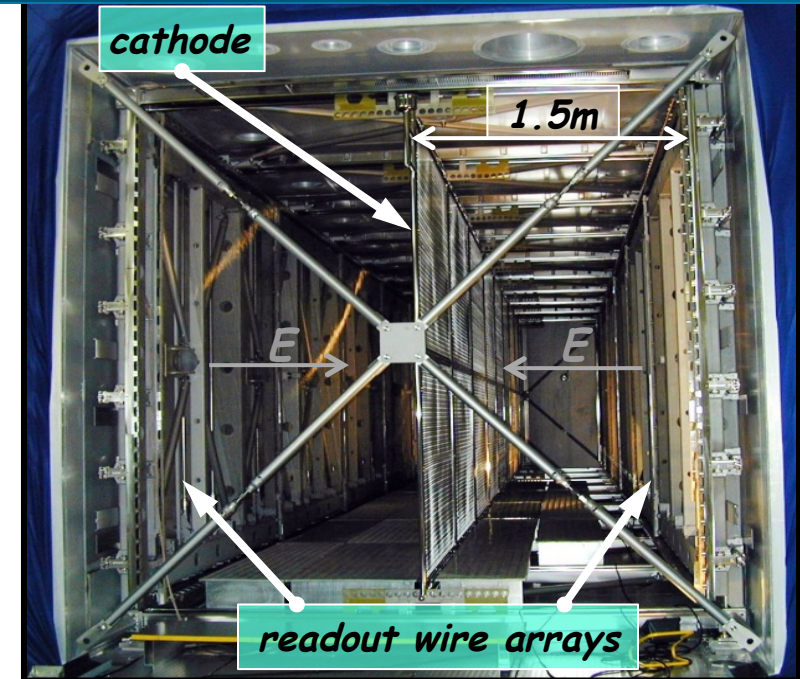
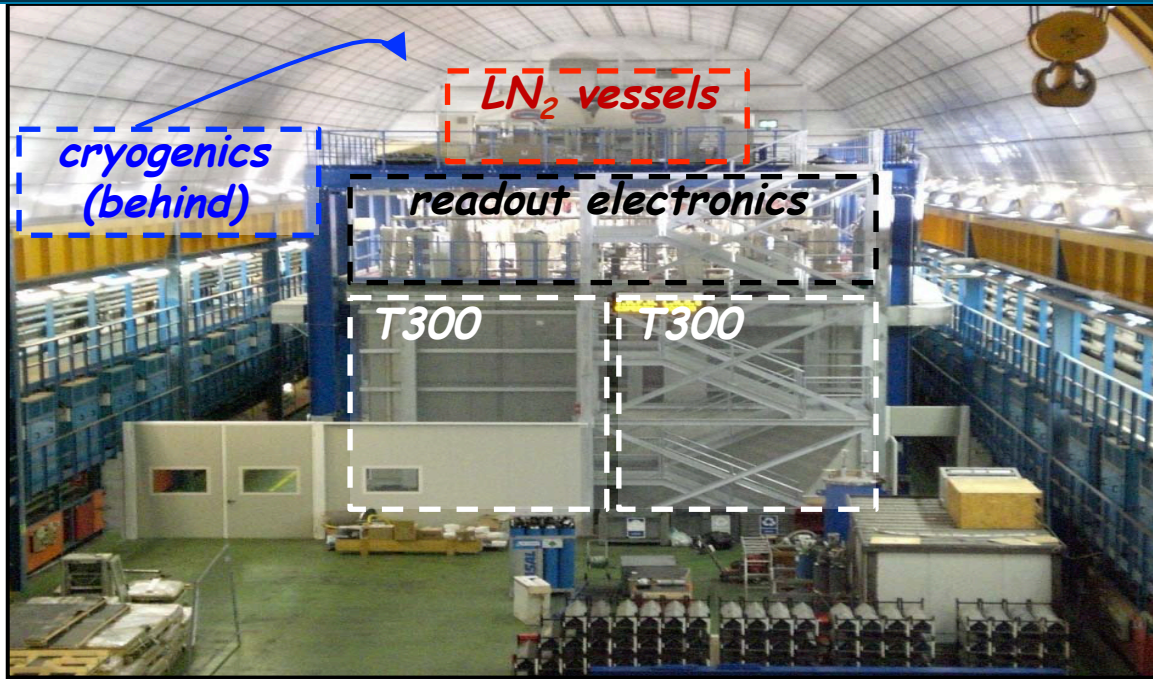
<sup>13</sup>Institute for Radioelectronics, Warsaw University of Technology, Warsaw, Poland

<sup>14</sup>Institute of Physics, University of Silesia, Katowice, Poland

<sup>15</sup>Institute of Theoretical Physics, Wrocław University, Wrocław, Poland

<sup>16</sup>National Centre for Nuclear Research, Warsaw, Poland

# ICARUS-T600 detector



## Two identical modules (T300)

- $3.6 \times 3.9 \times 19.6 = 275 \text{ m}^3$  each
- Liquid Ar active mass:  $\sim 476 \text{ t}$
- Drift length = 1.5 m (1 ms)
- HV = -75 kV;  $E = 0.5 \text{ kV/cm}$
- drift velocity =  $1.55 \text{ mm}/\mu\text{s}$
- Sampling time  $0.4 \mu\text{s}$  (sub-mm resolution in drift direction)

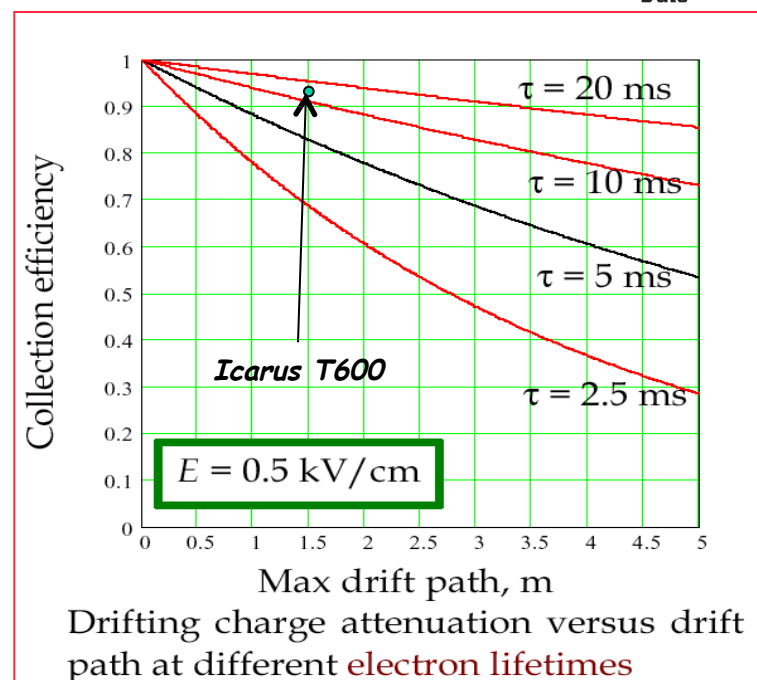
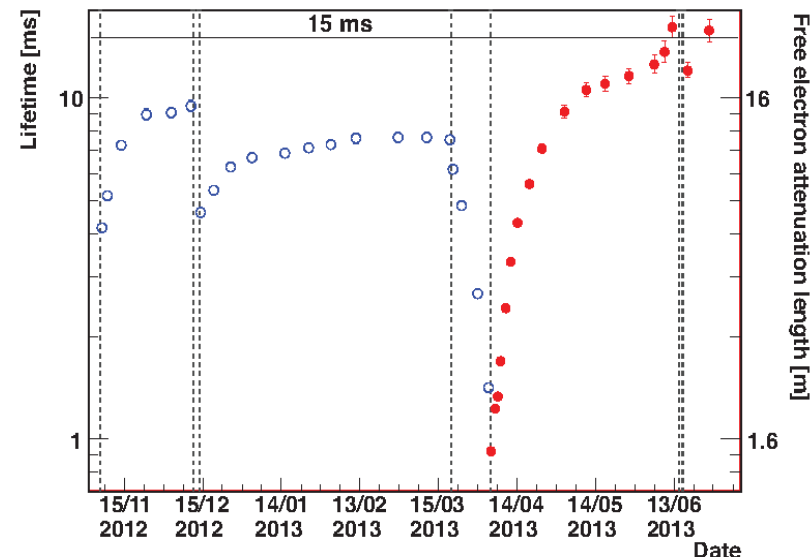
## 4 wire chambers

- 2 chambers per module
- 3 "non-destructive" readout wire planes per chamber wires at  $0, \pm 60^\circ$  (ind1, ind2, coll view)
- $\sim 54000$  wires, 3 mm pitch and plane spacing
- Charge measurement on collection plane
- 20+54 8" PMTs for scintillation light detection
  - VUV sensitive (128nm) with TPB wave shifter

# A key feature of LAr-TPC technique: very long $e^-$ mobility

- Level of electronegative impurities in LAr must be kept exceptionally low, in order to ensure  $\sim$ m long drift path of ionisation  $e^-$  without attenuation.
- New industrial purification methods have been developed to continuously filter and recirculate both in liquid ( $100 \text{ m}^3/\text{day}$ ) and gas ( $2.5 \text{ x/hour}$ ) phases.
- $\tau_e > 7 \text{ ms}$  measured during ICARUS run at LNGS  $\rightarrow$  12% max charge attenuation.  
 $\tau_e > 16 \text{ ms}$  ( $< 20 \text{ ppt O}_2 \text{ equiv.}$ ) in East cryo since April 4<sup>th</sup>, 2013 (new pump installed).
- $\tau_e \sim 21 \text{ ms}$  measured in the Icarino LAr-TPC (120 l) at INFN LNL.

*ICARUS has demonstrated the effectiveness of single phase LAr-TPC technique, paving the way to huge detectors ( $\sim 5 \text{ m}$  drift).*

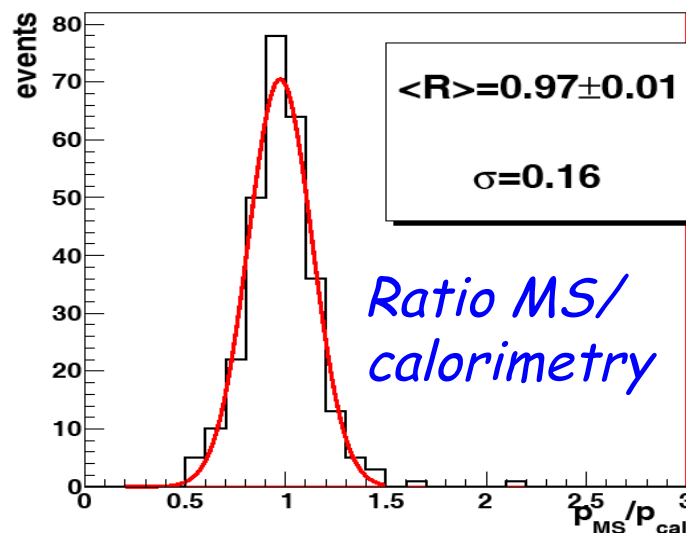


# ICARUS: the first large scale LAr physics experiment

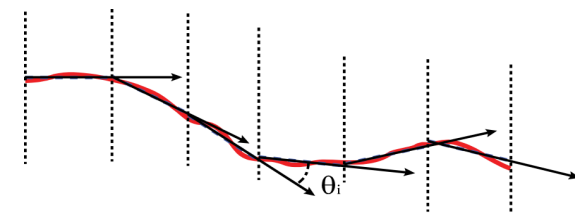
- Exposed to CNGS  $\nu$  beam (2010÷2012), collecting  $8.6 \times 10^{19}$  protons on target event statistics with a **detector live time > 93%**. Data taking also with c-rays to study atmospheric  $\nu$  and p-decay (0.73 kty exposure).
- During its operation, ICARUS demonstrated excellent detection properties.
  - Tracking device: precise 3D topology, high spatial resolution ( $\sim 1 \text{ mm}^3$ ), accurate ionization measurement.
  - Global calorimeter: total energy reconstruction is performed by charge integration, with excellent accuracy for contained events.
    - Low energy electrons:*  $\sigma(E)/E = 11\% / \sqrt{E(\text{MeV})} + 2\%$
    - Electromagnetic showers:*  $\sigma(E)/E = 3\% / \sqrt{E(\text{GeV})}$
    - Hadron shower (pure LAr):*  $\sigma(E)/E \approx 30\% / \sqrt{E(\text{GeV})}$
  - Local calorimeter: measurement of  $dE/dx$  allows remarkable  $e/\gamma$  separation and particle identification ( $dE/dx$  vs range) .
  - Momentum of non contained  $\mu$  determined via multiple Coulomb scattering ( $\Delta p/p \sim 16\%$  in the 0.4-4 GeV/c range).

# Measurement of muon momentum via multiple scattering

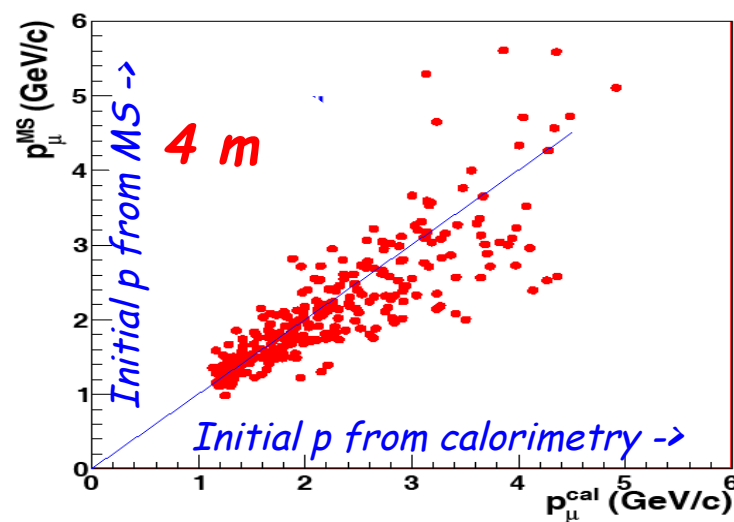
- RMS of deflection angle of  $\mu$ ,  $\theta_{RMS}$ , depends on momentum  $p$ , spatial resolution  $\sigma$  and track segmentation.
- The method has been tested on a sample of  $\sim 10^3$  stopping  $\mu$ 's from CNGS  $\nu$  interactions in upstream rock, comparing  $p^{MS}$  measured by MS with the corresponding calorimetric  $p^{CAL}$



$\mu$  track length:  $> 5m$   
Used length:  $4m$

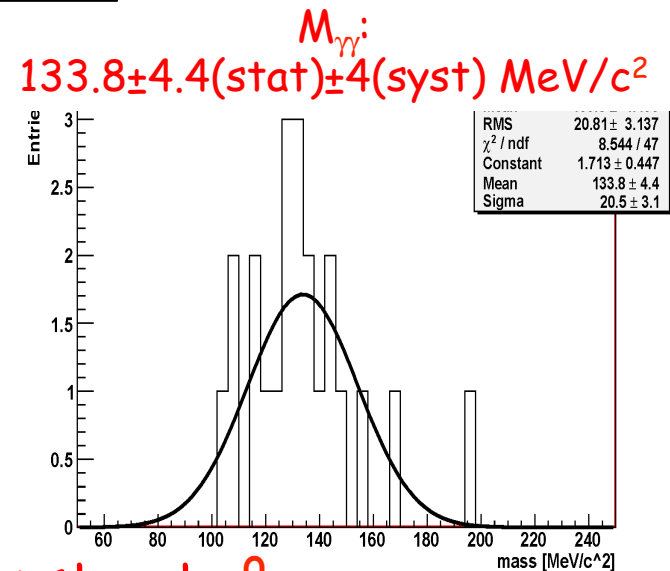
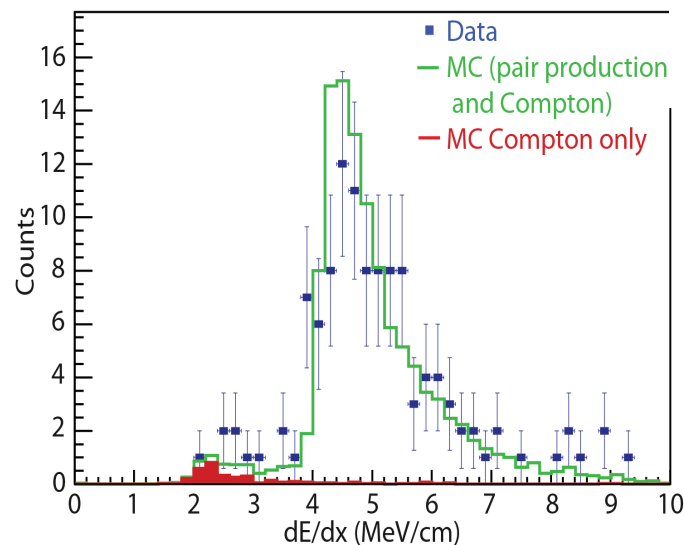
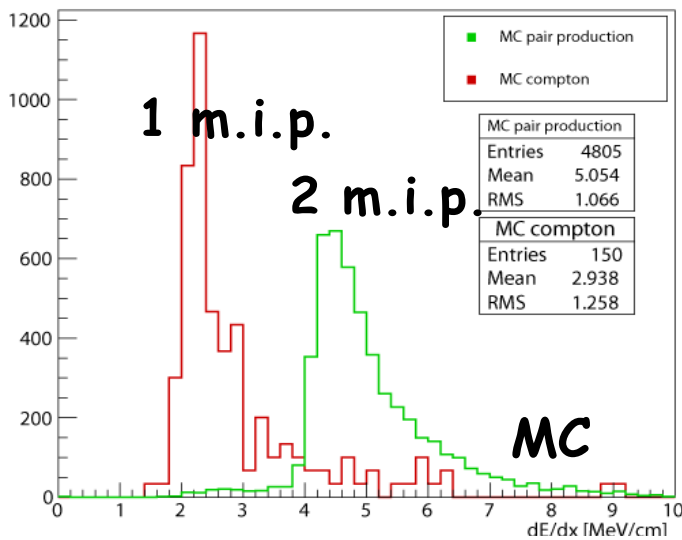
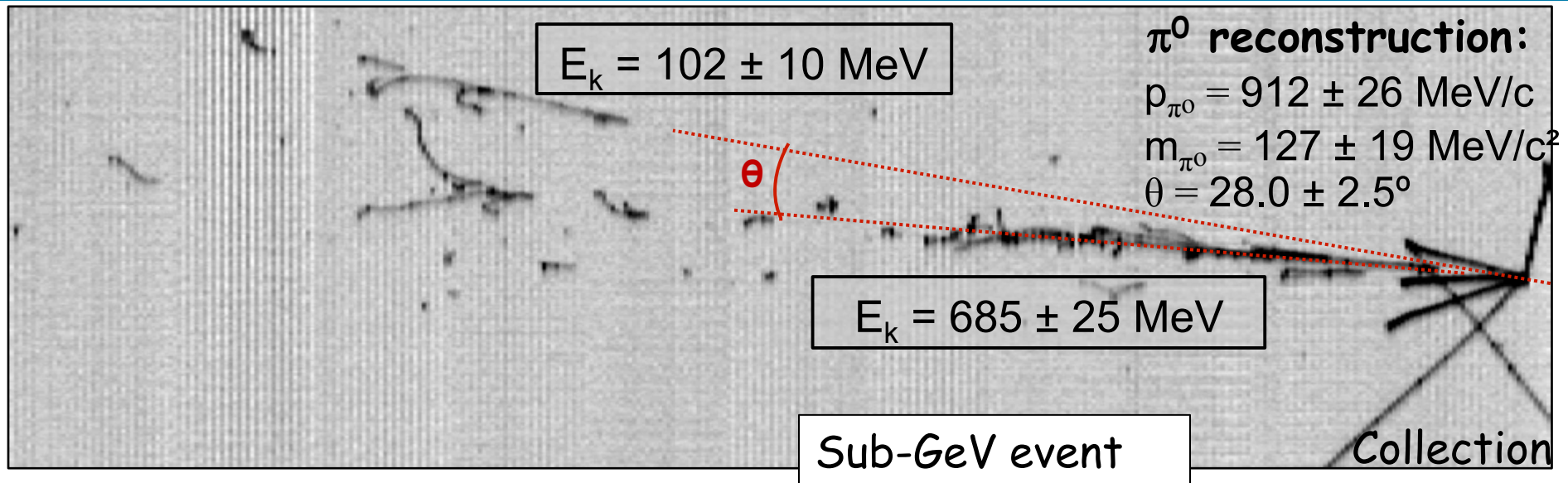


$$\theta_{RMS} \div \frac{13.6 MeV}{p} \sqrt{\frac{l}{X_0}} \oplus \frac{\sigma}{l^{3/2}}$$



*~16% resolution has been obtained in the 0.4-4 GeV/c momentum range of interest for the future short/long base-line experiments*

# $e/\gamma$ separation and $\pi^0$ reconstruction in ICARUS

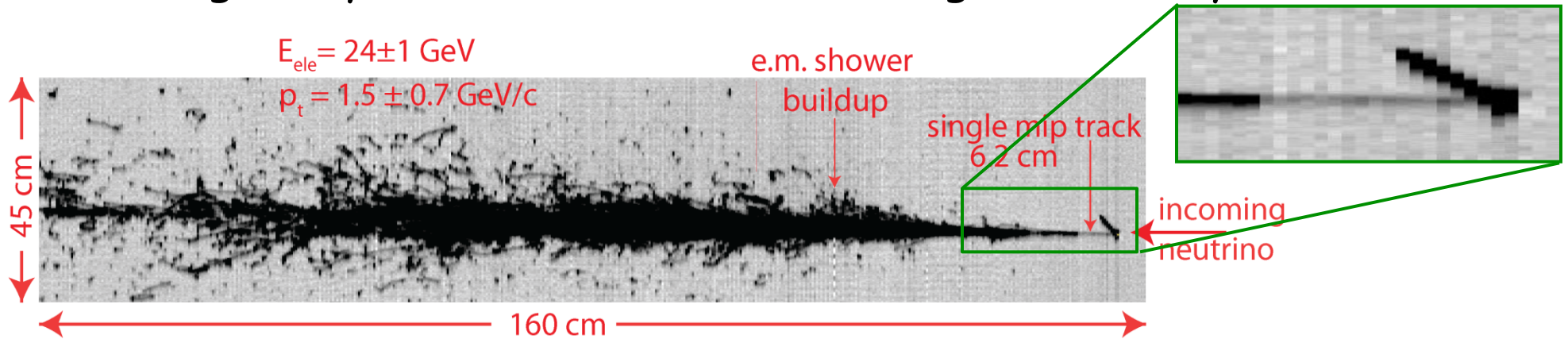


Unique feature of LAr to distinguish  $e$  from  $\gamma$  and reconstruct  $\pi^0$

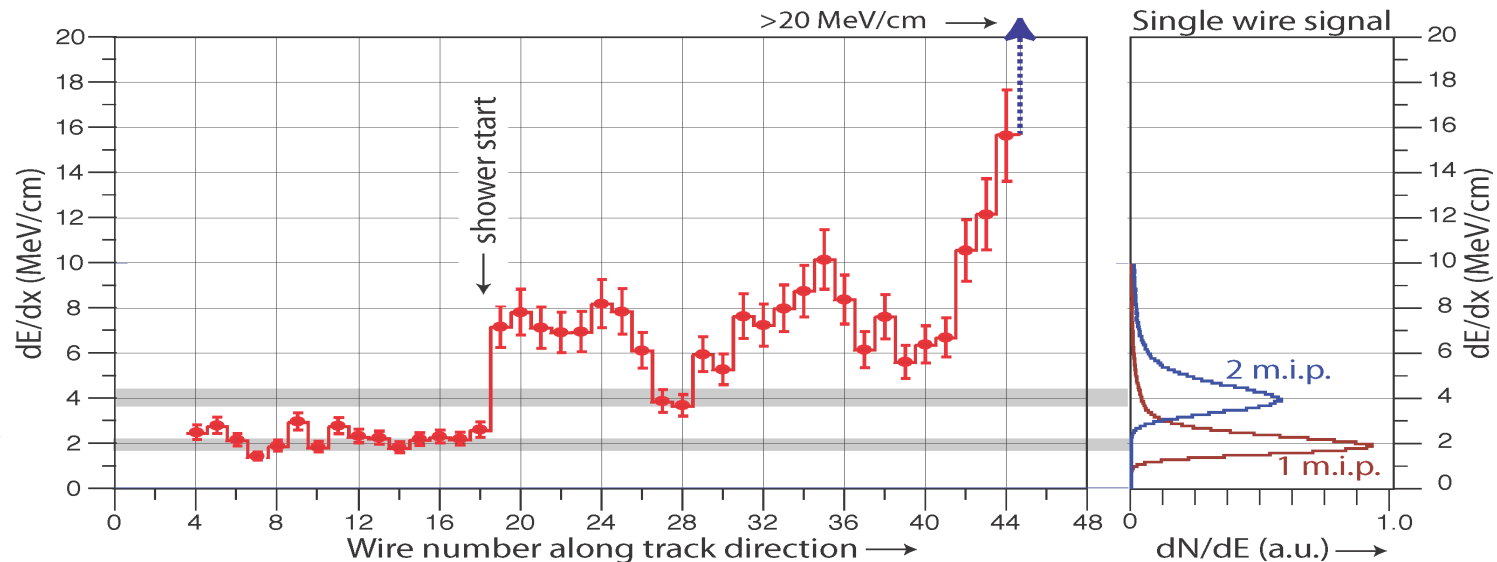
→ Negligible background from  $\pi^0$  in NC and  $\nu_\mu$  CC estimated from MC/scanning

# $\nu_e$ identification in ICARUS LAr-TPC

- The unique detection properties of LAr-TPC technique allow to identify unambiguously individual e-events with high efficiency.



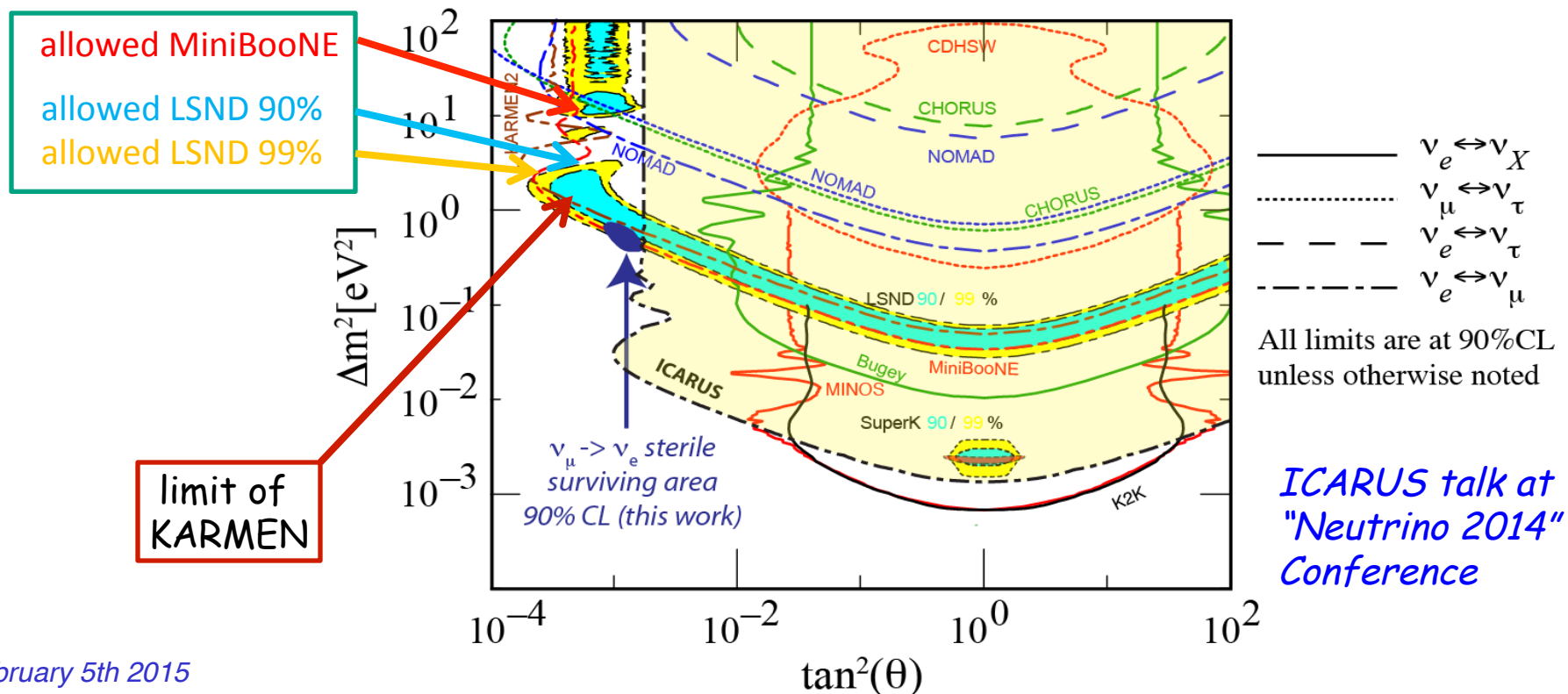
- The evolution of the actual  $dE/dx$  from a single track to an e.m. shower for the electron shower is clearly apparent from individual wires.



Single M.I.P. →

# LSND-like search by the ICARUS experiment at LNGS

- ICARUS searched for  $\nu_e$  excess related to a LSND-like anomaly, on the  $\nu_\mu$  CNGS beam ( $\sim 1\%$  intrinsic  $\nu_e$  contamination,  $L/E_\nu \sim 36.5$  m/MeV).
- Analysis on  $7.23 \times 10^{19}$  pot event sample provided the limit on the oscillation probability  $P(\nu_\mu \rightarrow \nu_e) \leq 3.85$  (7.60)  $\times 10^{-3}$  at 90 (99) % C.L.
- ICARUS result indicates a very narrow region of the parameter space ( $\Delta m^2 \approx 0.5 \text{ eV}^2$ ,  $\sin^2 2\vartheta \approx 0.005$ ) where all experimental results can be accommodated at 90% CL.



# Persisting anomalies in the neutrino sector

- Three main classes of anomalies have been reported, namely the apparent **disappearance signal** in the anti- $\nu_e$  events
  - (1) detected from near-by nuclear reactors, where the observed to predicted event rate is  $R = 0.938 \pm 0.023$  and
  - (2) from Mega-Curie k-capture calibration sources in the experiments to detect solar  $\nu_e$  with  $R = 0.86 \pm 0.05$ , and, in addition,
  - (3) observation of **excess signals** of  $\nu_e$  electrons from muon neutrinos from particle accelerators (the LSND effect:  $3.8 \sigma$  evidence for oscillations).
- These three independent signals may all point out to the possible existence of at least a fourth non standard and heavier “sterile” neutrino state driving oscillations at a small distances, with  $\Delta m_{\text{new}}^2$  of the order of  $\approx 1 \text{ eV}^2$  and relatively small  $\sin^2(2\vartheta_{\text{new}})$  mixing angles.
- According to Planck measurement and Big Bang cosmology, at most one sterile  $\nu$  is expected, with  $\Delta m^2 < 0.5 \text{ eV}^2$ .

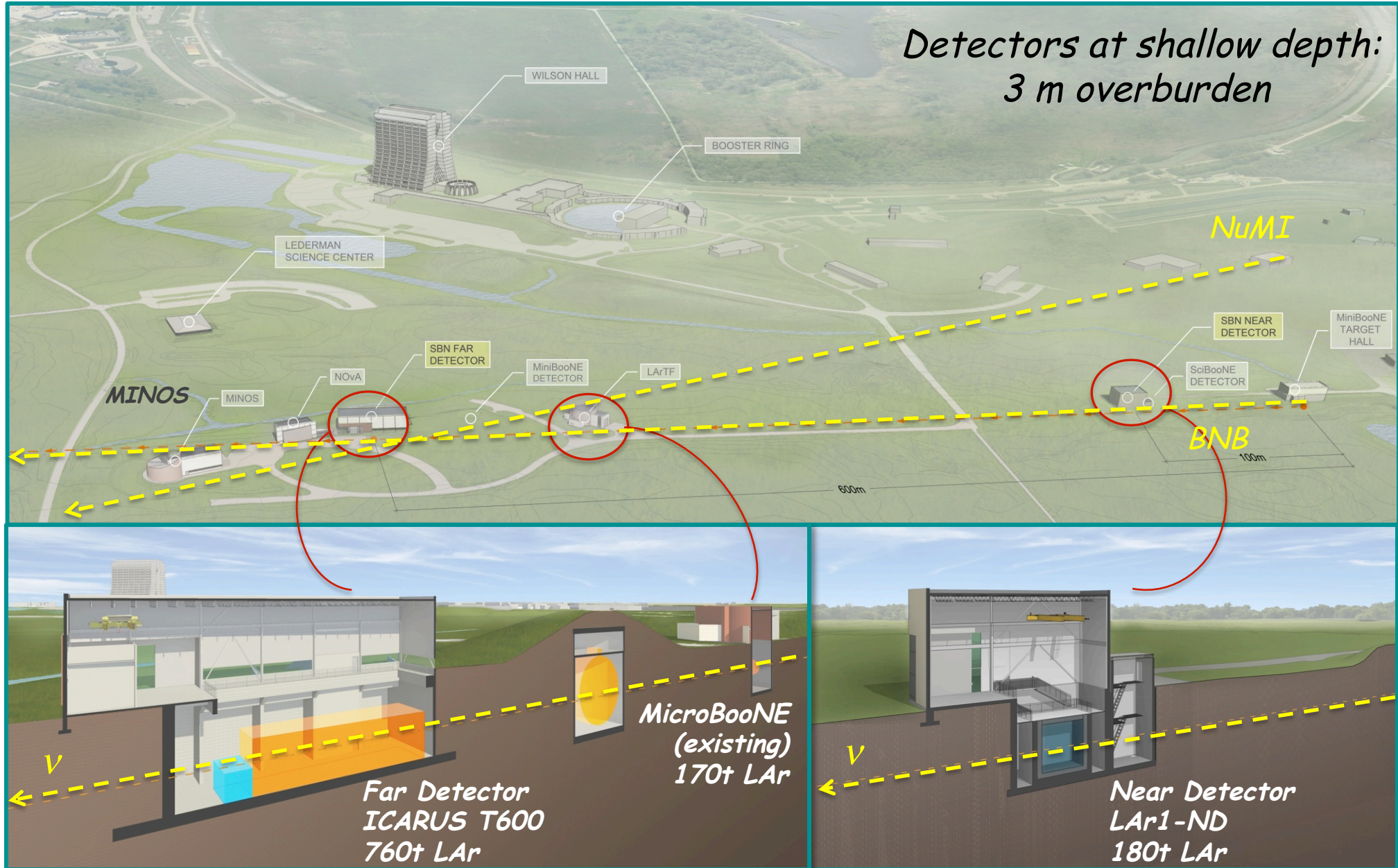
# Sterile neutrino search at the FNAL Booster $\nu$ beamline

- An ultimate experiment with multiple LAr-TPCs exposed to FNAL Booster  $\nu$  beam ( $\langle E_\nu \rangle \sim 0.8$  GeV) has been proposed as definitive answer to the “sterile neutrino puzzle”. Conceptual Design Report, joint ICARUS/LAr1-ND/MicroBooNE effort, has been presented to FNAL PAC (Jan 15<sup>th</sup>).
- It will exploit three LAr-TPC detectors at different distances from target: LAr1-ND (82 t active mass), MicroBooNE (89 t) and ICARUS T600 (476 t) at 110, 470 and 600 m.
- The experiment will likely clarify both LSND/MiniBooNE and Gallex/reactor anomalies by precisely and independently measuring both  $\nu_e$  appearance and  $\nu_\mu$  disappearance, mutually related through the relation

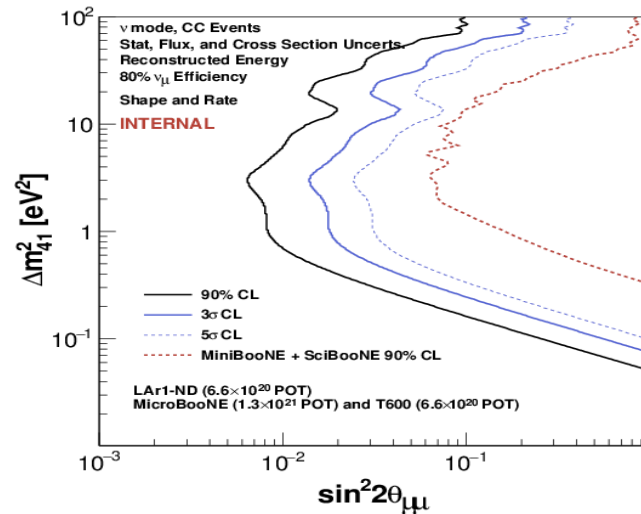
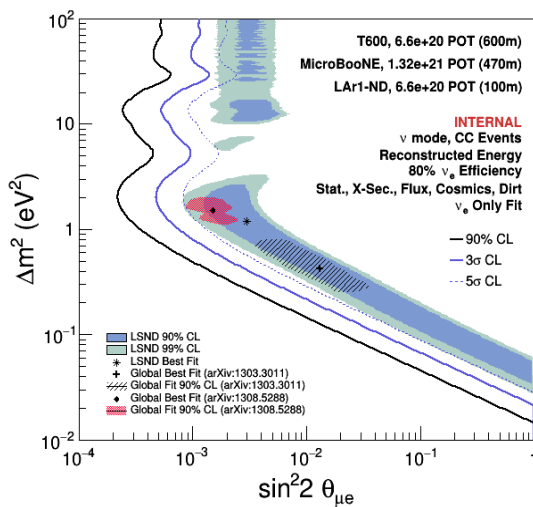
$$\sin^2(2\vartheta_{\mu e}) \leq \frac{1}{4} \sin^2(2\vartheta_{\mu x}) \sin^2(2\vartheta_{ex})$$

- In absence of “anomalies”, the three detector signals should be a closer copy of each other for all experimental signatures. However, the intrinsic  $\nu_e$  events with a disappearance signal (if f.i. confirmed by reactors) may result in the reduction of a superimposed LSND  $\nu_e$  signal. These two effects can be disentangled by changing the intrinsic  $\nu_e$  beam contamination with different beamline optics (horn and decay tunnel length).

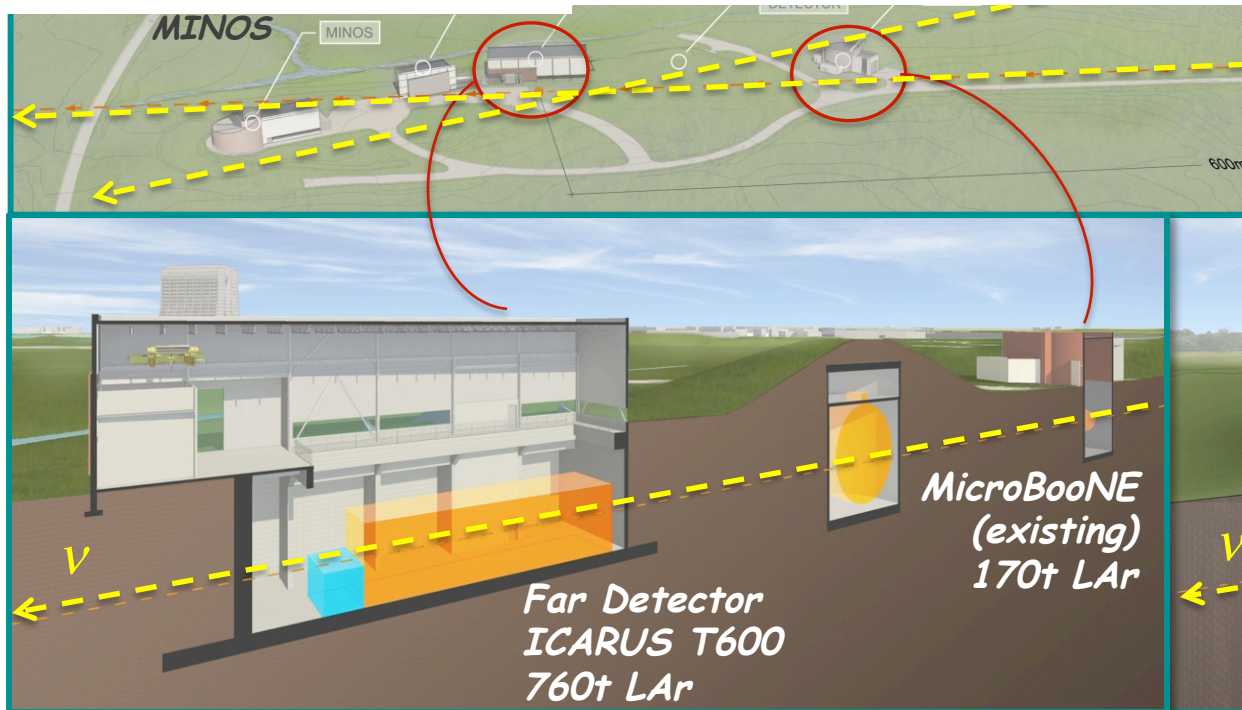
# Proposed SBN layout at FNAL BNB and related sensitivities



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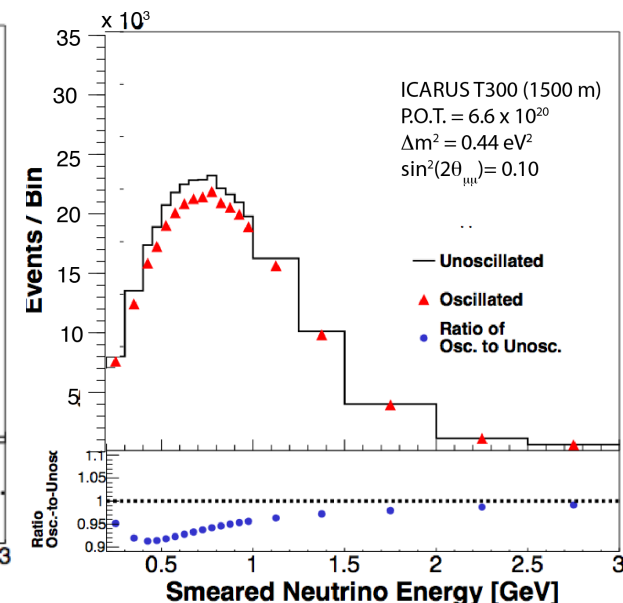
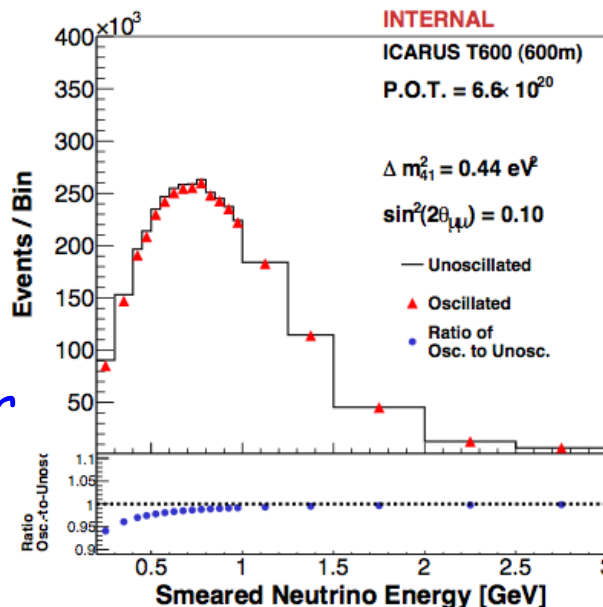


- 3 years - 6.6  $10^{20}$  pot BNB positive focusing
- The LSND 99% CL region is covered at the  $\sim 5\sigma$  level
- SBN can extend sensitivity by 1 order of magnitude beyond SciBooNE+MiniBooNE
- appearance ( $\nu_e$ ) and ( $\nu_\mu$ ) disappearance analyses currently performed independently



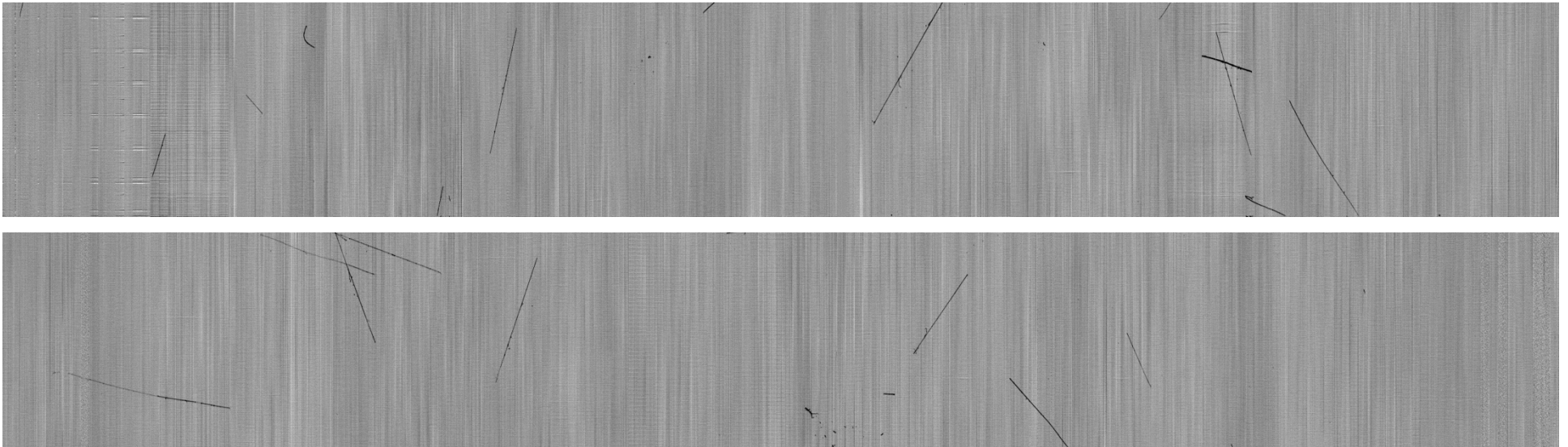
# $\nu_\mu$ disappearance measurement

- Within 3+1 model, the most relevant and solid result is LSND, where  $\sin^2 2\vartheta_{e\mu} = 4|U_{e4}|^2/|U_{\mu4}|^2 \approx 1.5 \cdot 10^{-3}$ . If LSND is confirmed, both  $\nu_e$  and  $\nu_\mu$  disappearance are present, since  $\sin^2 2\vartheta_{ee} = 4|U_{e4}|^2 (1 - |U_{e4}|^2)$  and  $\sin^2 2\vartheta_{\mu\mu} = 4|U_{\mu4}|^2 (1 - |U_{\mu4}|^2)$
- Reactor experiments presently claim  $\sin^2 2\vartheta_{ee} \approx 0.12$ ,  $|U_{e4}|^2 = 0.03$ .
- From LSND and assuming naively muon-electron universality, we expect at FNAL  $\sin^2 2\vartheta_{ee} = \sin^2 2\vartheta_{\mu\mu} \approx 0.08$ , about  $\frac{1}{2}$  of the present reactor data and Mega-sources much smaller than claimed.
- For  $\Delta m^2 < 0.5 \text{ eV}^2$  the  $\nu_\mu$  disappearance effect at 600 m will be limited at the lowest  $\nu$  energy bins 0.2-0.4 GeV.
- In order to amplify the effect, we may move at a later stage one ICARUS T300 to 1500 m distance.



# Facing a new situation: the LAr-TPC near the surface

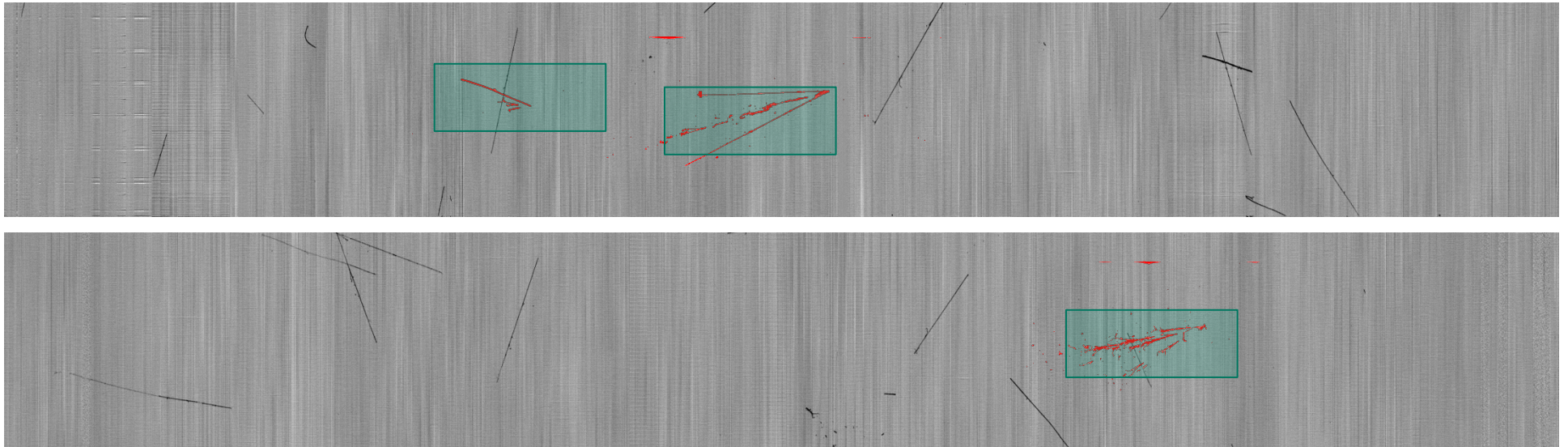
- At shallow depths several uncorrelated cosmic rays will occur in T600 during the 1 ms drift window readout at each triggering event:  $\sim 12$  muon tracks per drift in each ICARUS half module were measured on surface (Pavia 2001).



*Cosmic rays (PV)*

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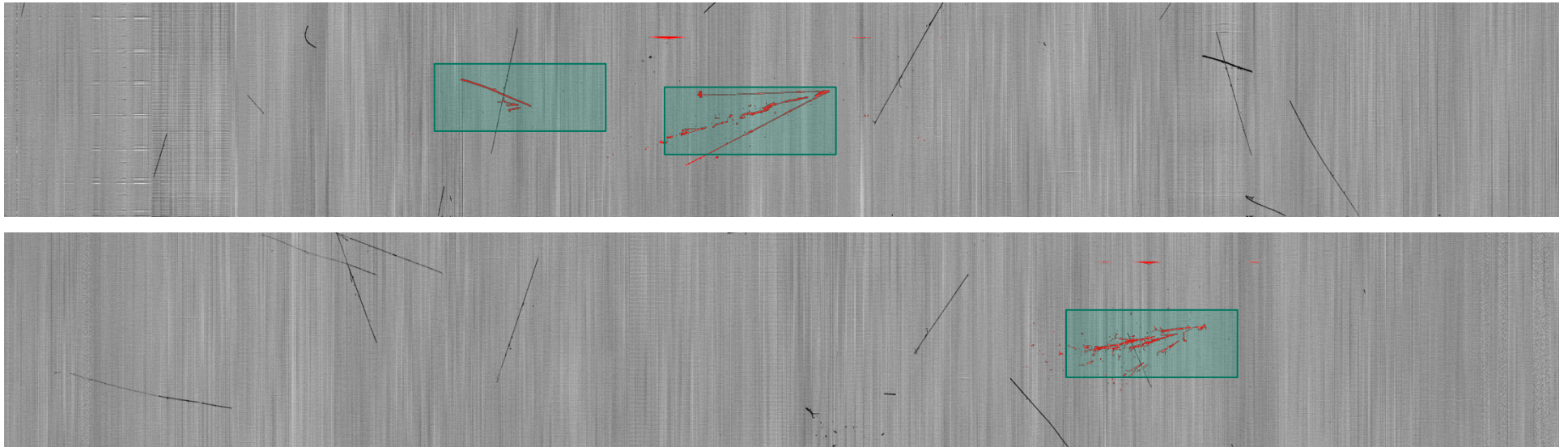
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*Cosmic rays (PV) + low energy CNGS beam events*

# Facing a new situation: the LAr-TPC near the surface

- At shallow depths several uncorrelated cosmic rays will occur in T600 during the 1 ms drift window readout at each triggering event:  $\sim 12$  muon tracks per drift in each ICARUS half module were measured on surface (Pavia 2001).
- This represents a new problem compared to underground operation at LNGS since, in order to reconstruct the true position of each track, it is necessary to associate precisely the related timing of each element of the TPC image with respect to the trigger time.



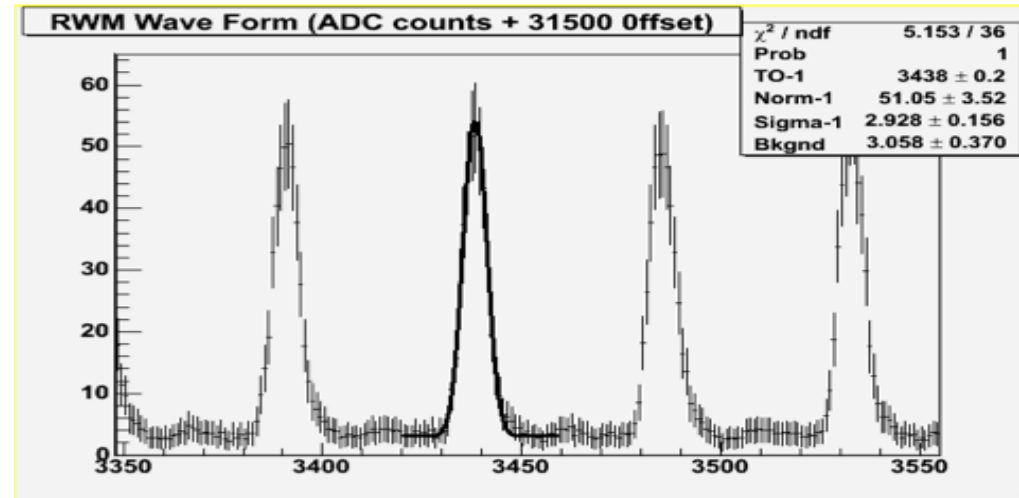
*Cosmic rays (PV) + low energy CNGS beam events*

# Cosmogenic background mitigation

- Photons associated with cosmic  $\mu$  represent a serious background for the  $\nu_e$  appearance search, since electrons generated in LAr via Compton scattering / pair production can mimic a  $\nu_e$ CC signal.
- In order to strongly mitigate the cosmogenic background, all the c-ray particles entering the detector must be unambiguously identified. This can be achieved by implementing a Cosmic Rays Tagging around the LAr active volume that provides an external timing of each track to be combined with the TPC reconstructed image. This system could consist either of external RPCs or plastic scintillation counters or internal readout plates detecting ionization signals.
- For instance the adoption of a full coverage muon tagging system with 95% detection efficiency of single muon hit could ensure 99% efficiency in c-rays identification in T600, relying on double crossing of muons (only 15% are expected to stop in LAr).

# Further mitigation of cosmogenic background

- Further rejection capabilities will come from precise timing information from internal scintillation light detectors. A  $\sim 1$  ns accuracy will enable exploiting the bunched structure of the Booster p beam within spill (2 ns wide bunches every 19 ns).
- Additional background mitigation strategies, exploiting the topological capability of the LAr-TPC, will be also applied to identify photons inside LAr active volume associated with cosmic muons.
- This requires the development of automatic tools to efficiently select, identify and reconstruct the neutrino interactions among the millions events triggered by cosmics (to be compared with the  $\sim 3000$  events collected by ICARUS during CNGS run at LNGS!).

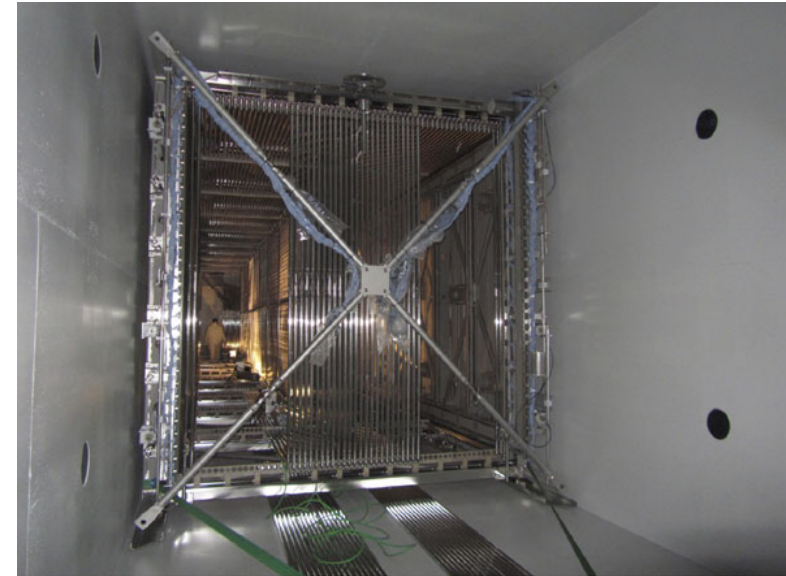


# A continuing neutrino program

- The recent success of ICARUS-CNGS2 experiment has conclusively demonstrated that LAr-TPC is *the leading technology for future short/long baseline accelerator driven neutrino physics*.
- INFN has signed a Memorandum of Understanding for **WA104 project at CERN** and just concluded an important cooperation agreement for a short baseline experiment in the framework of the US-LBNF collaboration, involving the long term realization of a truly large mass, LAr-TPC detector.
- During its operation in the Short Baseline Neutrino Oscillation Program **SBN at Fermilab**, ICARUS will collect also  $\nu_e$ CC events with the NUMI Off-Axis beam peaked at  $\sim 2$  GeV, which will be an asset for the LBNF project.
- These activities represent as well an opportunity to further develop the LAr-TPC technique in view of the ultimate realization of the LBNF detector, with:
  - accurate determination of cross sections in liquid Argon;
  - experimental study of all individual CC and NC channels;
  - realization of sophisticated algorithms to improve the automatic identification of neutrino interactions.

# WA104 Project at CERN: overhauling of the T600

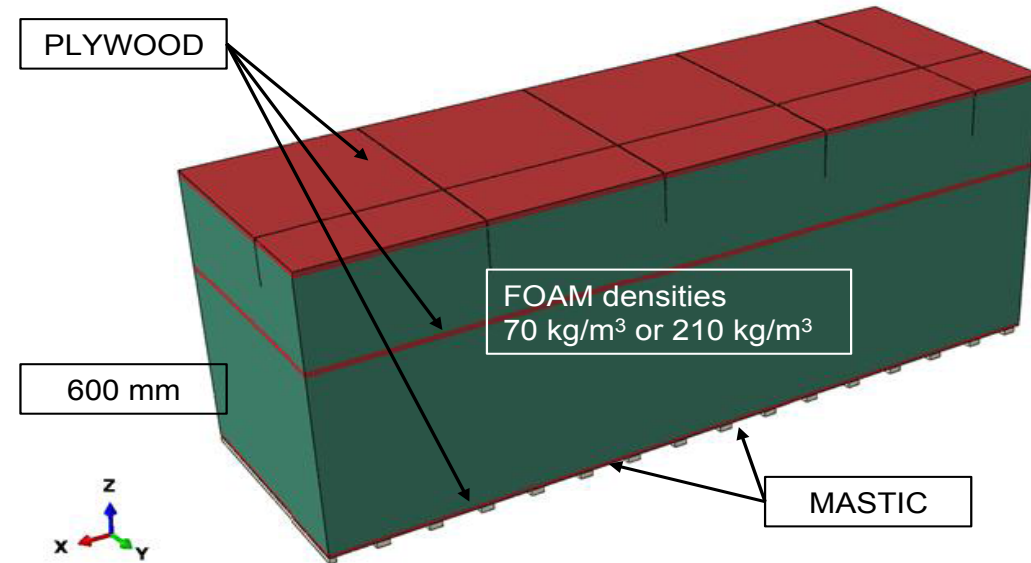
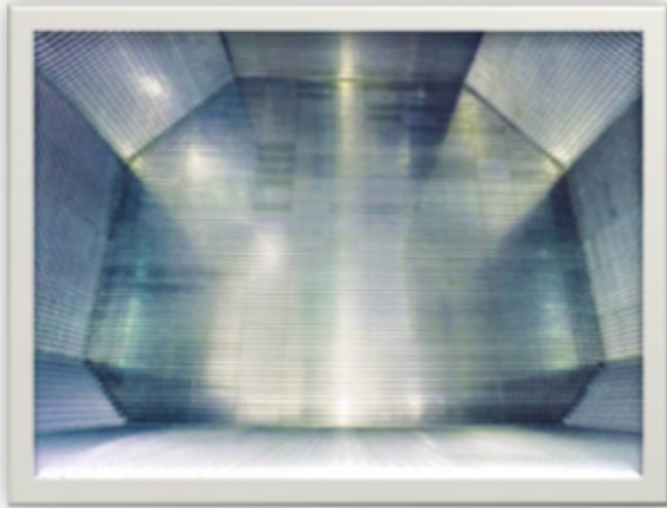
- The T600, already moved to CERN, is being upgraded introducing technology developments **while maintaining the already achieved performance**:
  - new cold vessels and new purely passive insulation;
  - refurbishing of the cryogenic and purification equipment;
  - new cathode with better planarity;
  - upgrade of the light collection system;
  - new faster, higher-performance read-out electronics.
- In parallel, the muon tagging system will be designed and constructed.
- Fully automatic tools for event reconstruction have to be developed.
- The detector is expected be transferred to FNAL before end of 2016 for installation, commissioning and start of data taking with  $\nu$  beam.



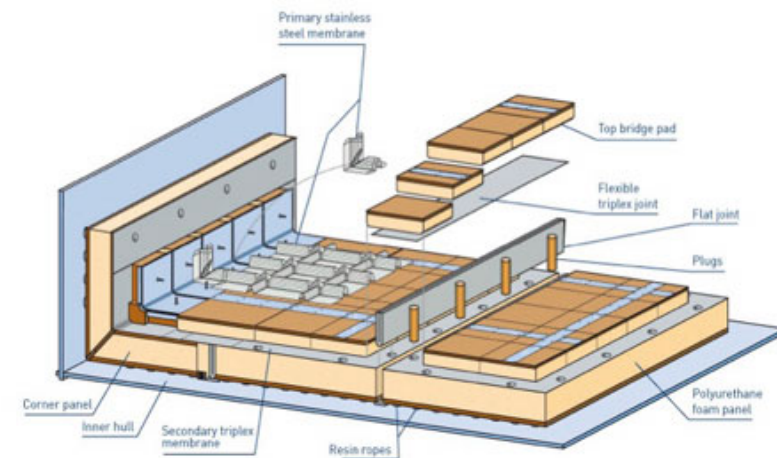
# Transfer of ICARUS-T600 from LNGS to CERN



# New Thermal Insulation

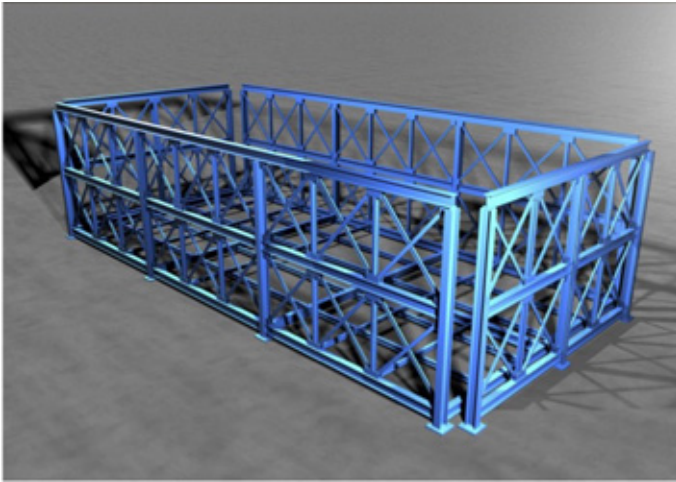


- Purely passive insulation chosen for the installation at CERN, coupled to standard cooling shield with boiling Nitrogen;
- Technique developed for 50 years and widely used for large industrial storage vessels and ships for liquefied natural gas.
- Expected heat loss through the insulation:  $T600 \approx 6.6 \text{ kW}$
- No internal membrane is required



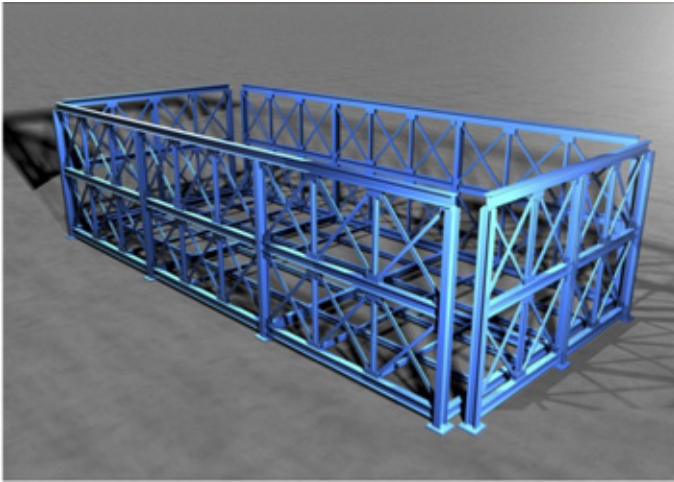
# New T600 layout

*Warm vessel cage*

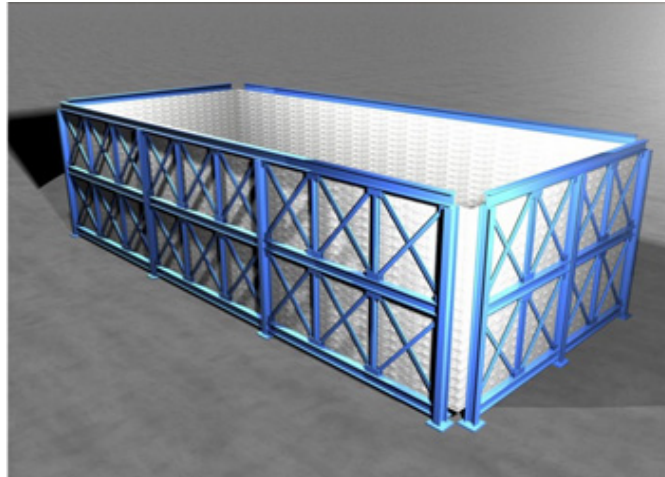


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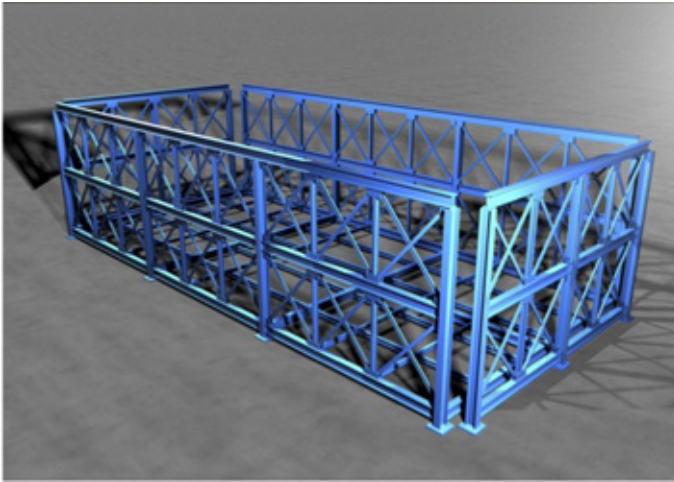


*External skin*

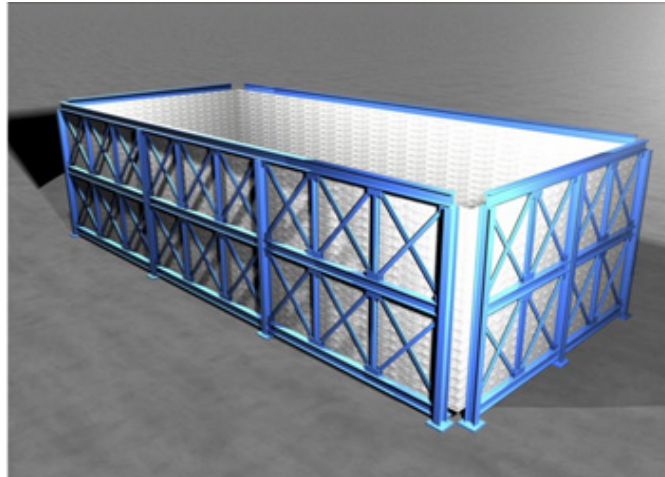


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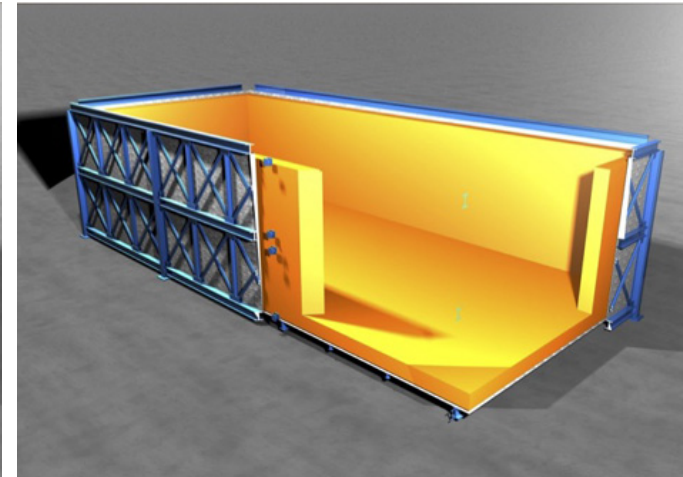
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*External skin*

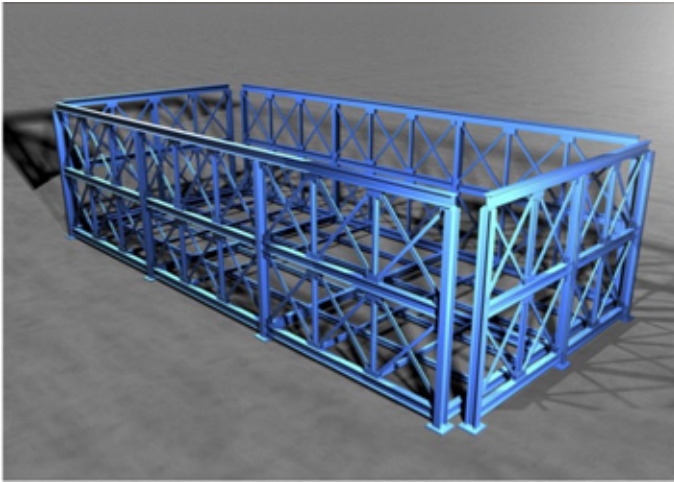


*Insulation panels*

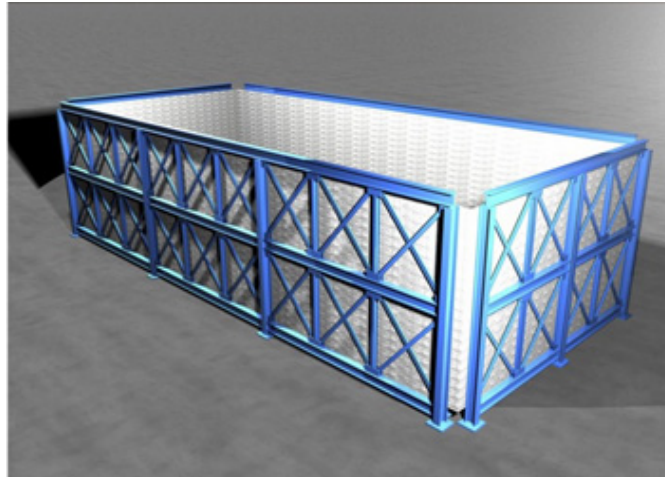


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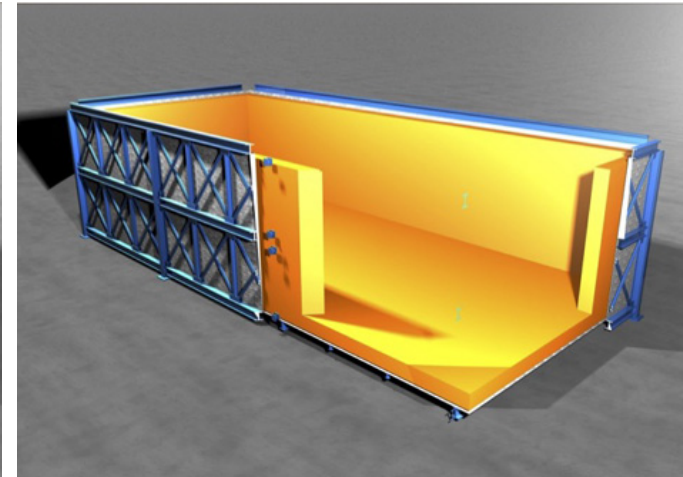
*Warm vessel cage*



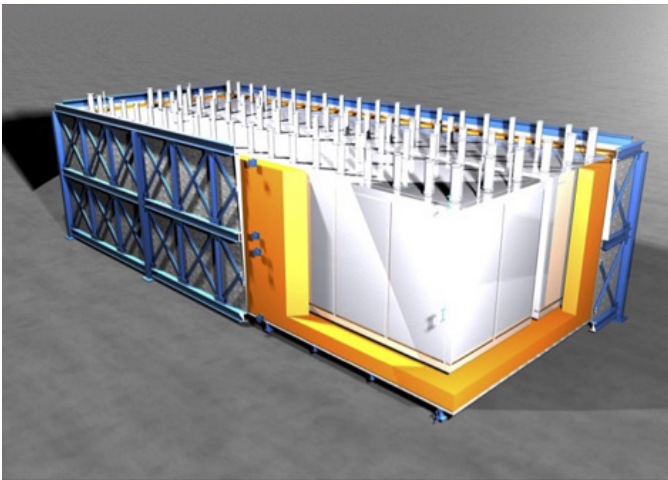
*External skin*



*Insulation panels*

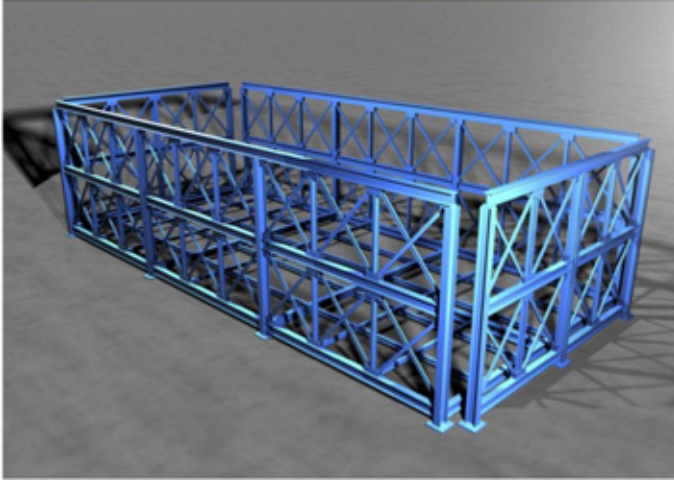


*T600 modules*

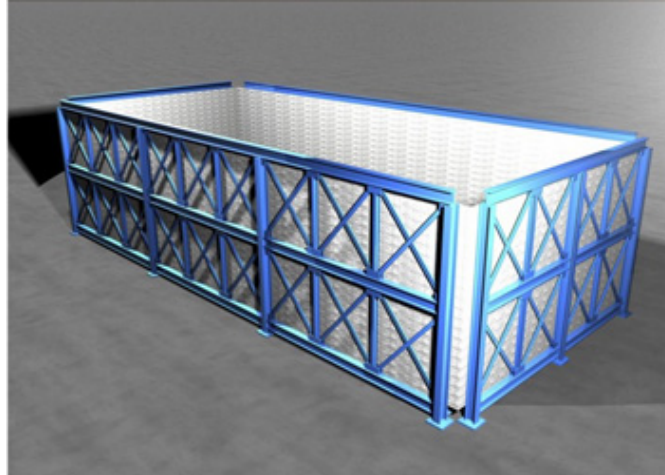


# New T600 layout

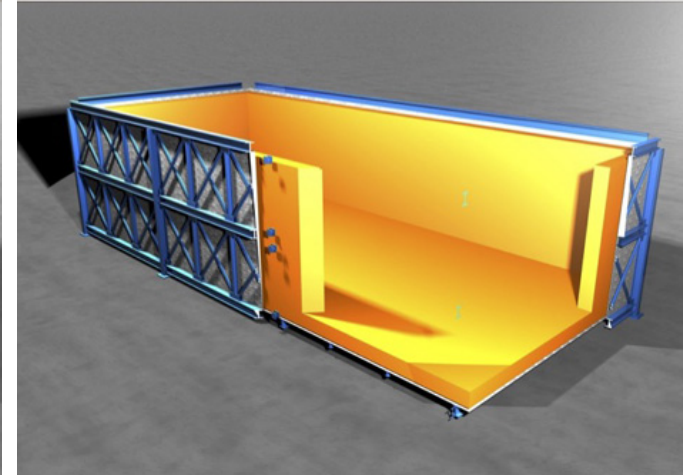
*Warm vessel cage*



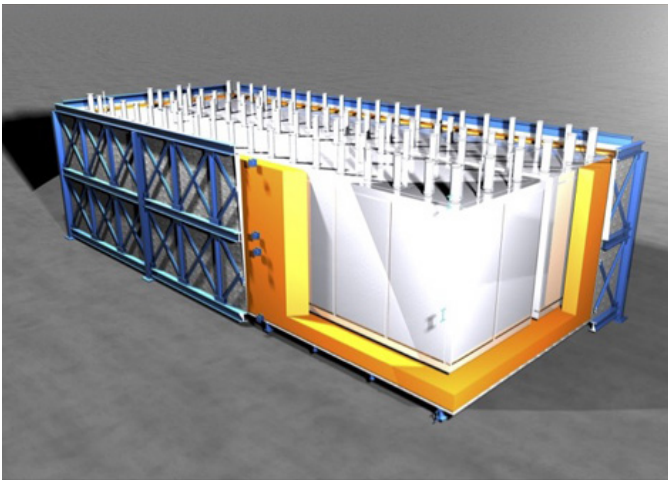
*External skin*



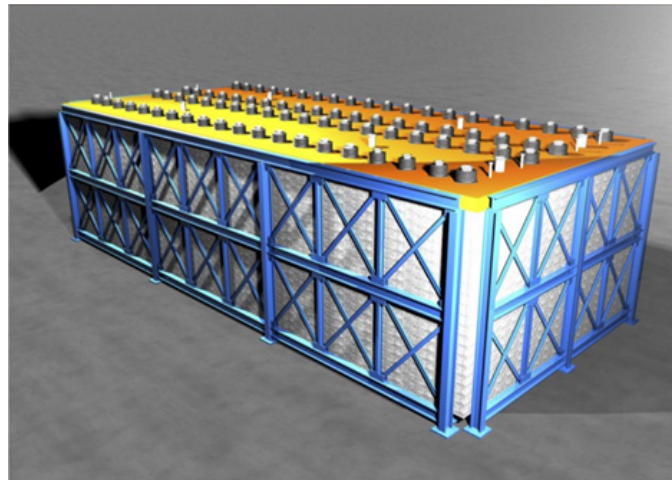
*Insulation panels*



*T600 modules*

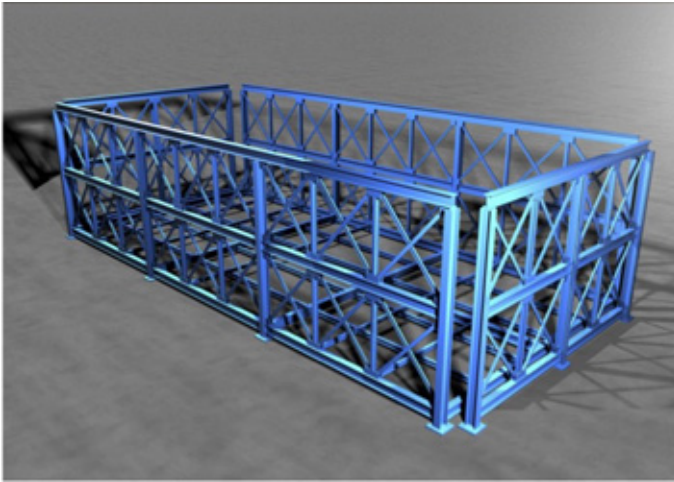


*Insulation top*

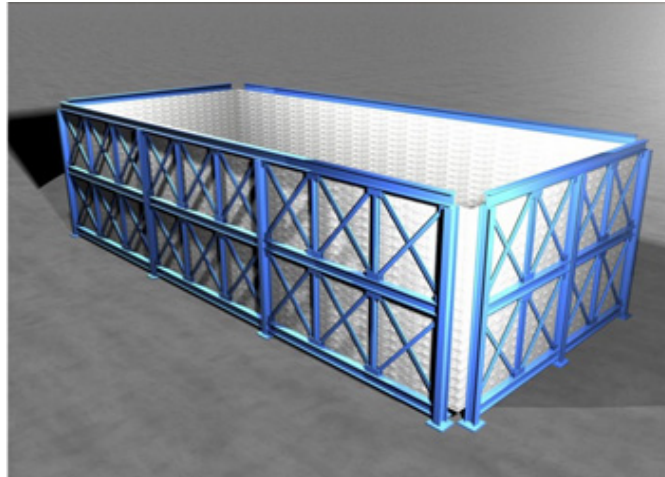


# New T600 layout

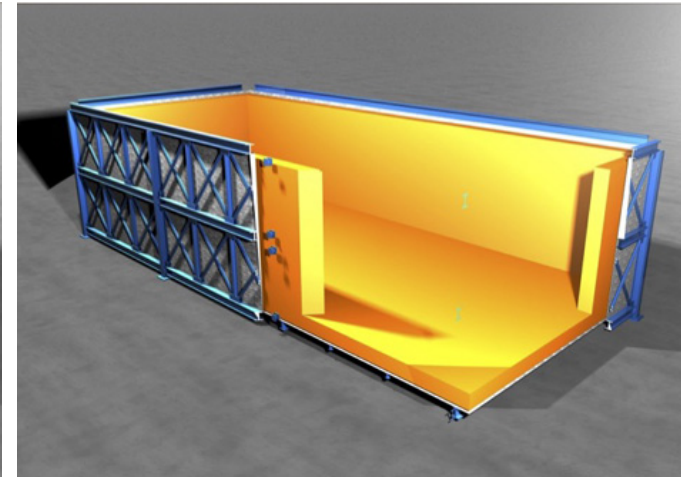
*Warm vessel cage*



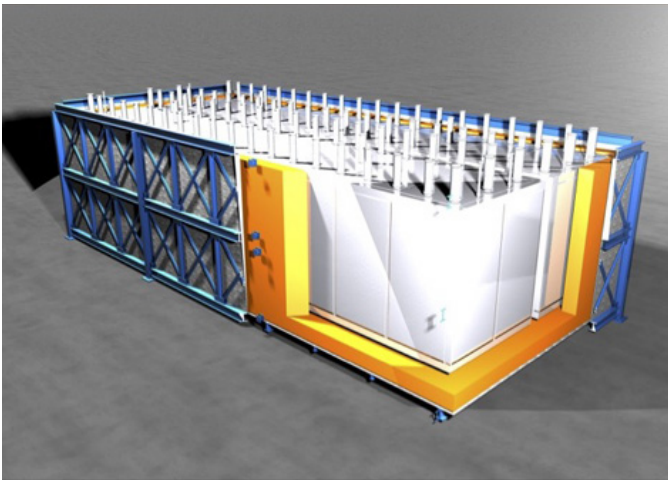
*External skin*



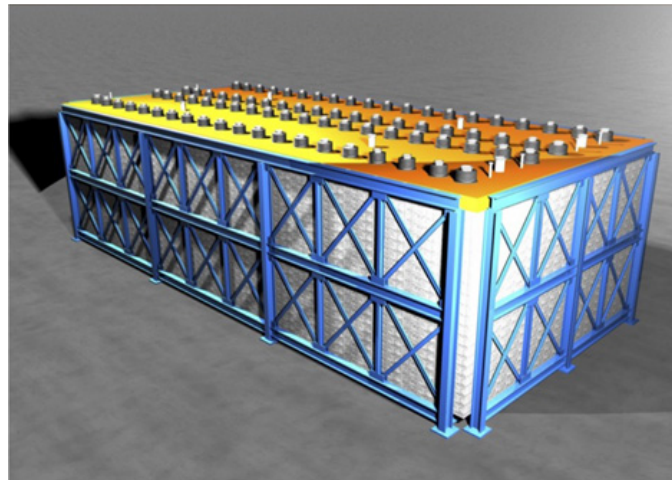
*Insulation panels*



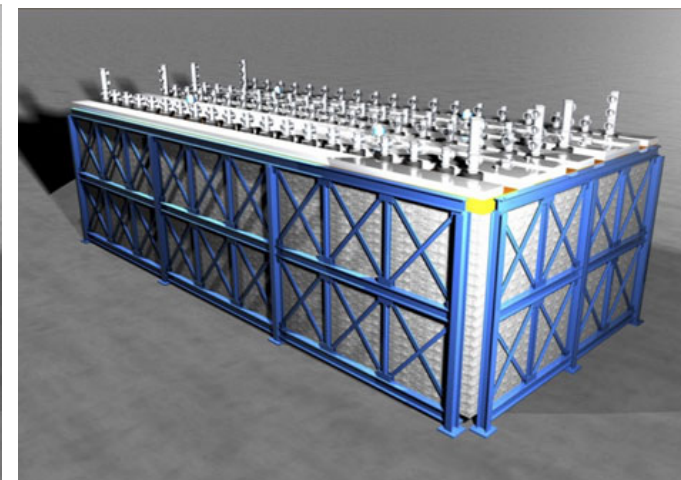
*T600 modules*



*Insulation top*



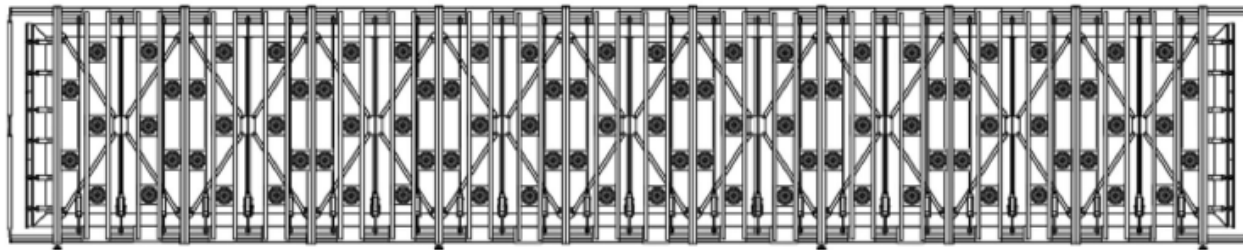
*Top flanges (final layout)*



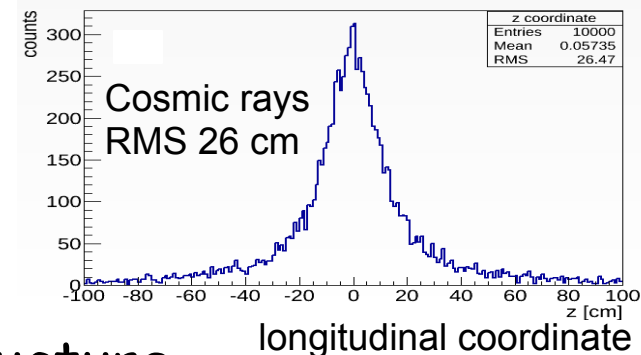
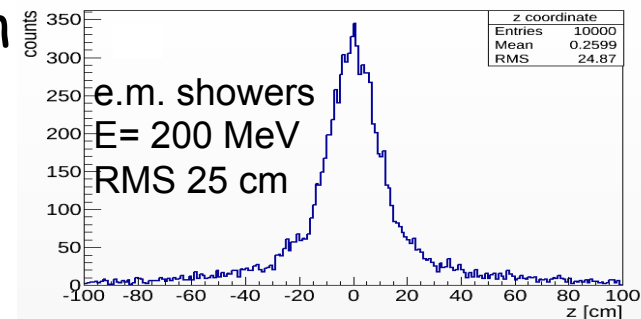
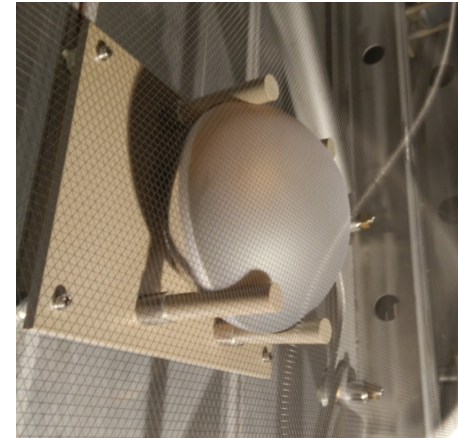
# Upgrade of the light collection system

Large surface 8" PMTs will be adopted as in T600, but major improvements in space/time event localization capabilities are required to reject cosmogenic bckg:

- higher quantum efficiency (QE);
- improved photocathode coverage > 5%. F.i. a 90 PMTs per TPC layout, compatible with present mechanical structure, allows to obtain longitudinal resolution < 0.5 m (MC simulation with 5% effective QE).

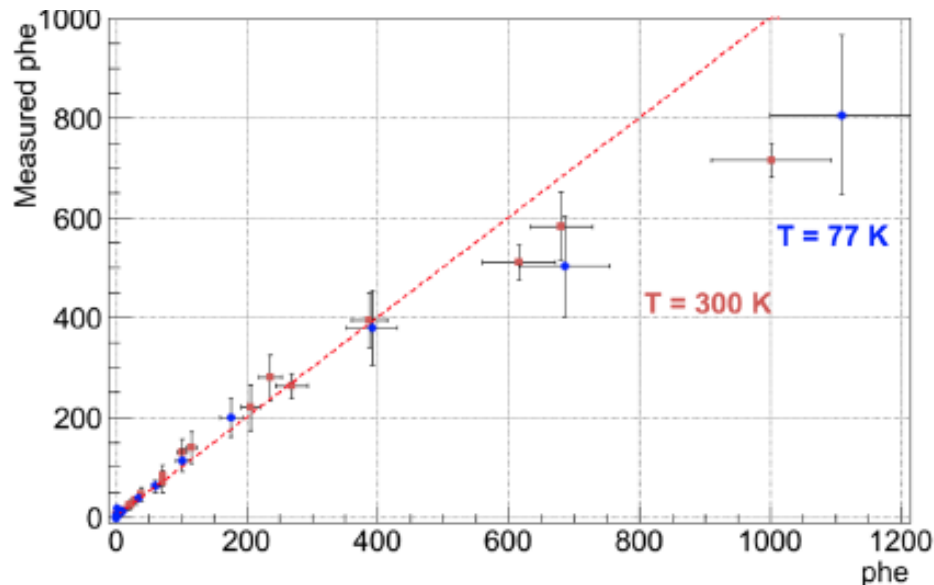


- new PMT voltage divider, to prevent induced spurious signals on TPC wire planes;
- better performance readout electronics, with ~ ns resolution, to exploit the bunched beam structure.

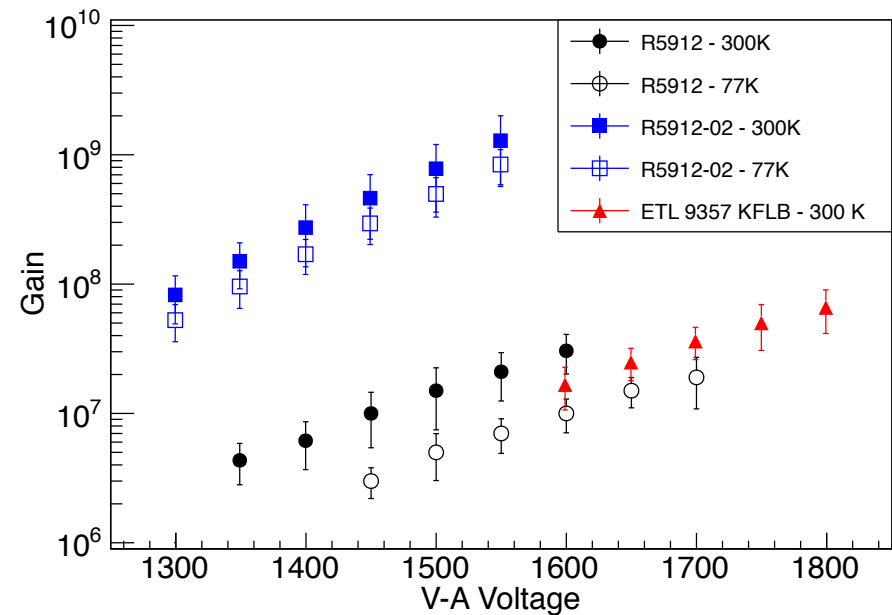


# Results on PMT characterization

- Hamamatsu 8" R5912 and ETL 9357 KFLB are being tested in:
  - gain and linearity as a function of temperature;
  - effective Quantum Efficiency with TPB coating (wavelength shift);
  - response uniformity of the photocathode;
  - dark noise level.

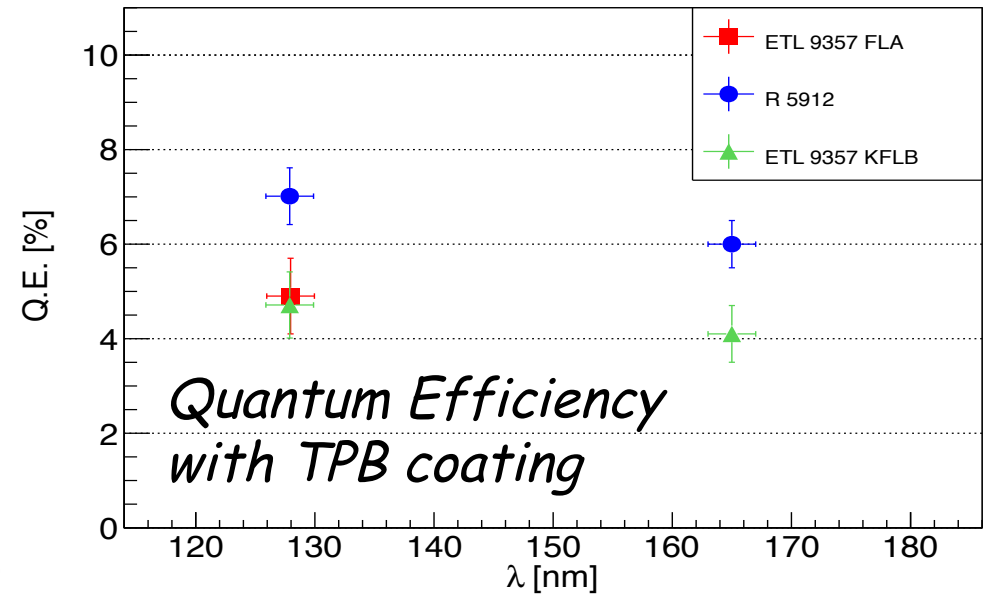
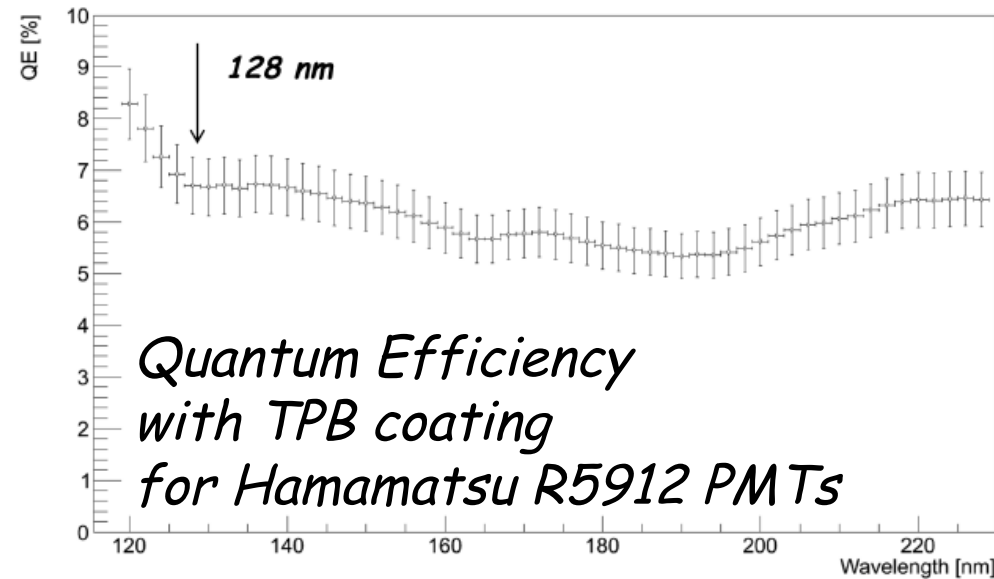


*Linearity at cryogenic temperatures for Hamamatsu R5912 PMTs*



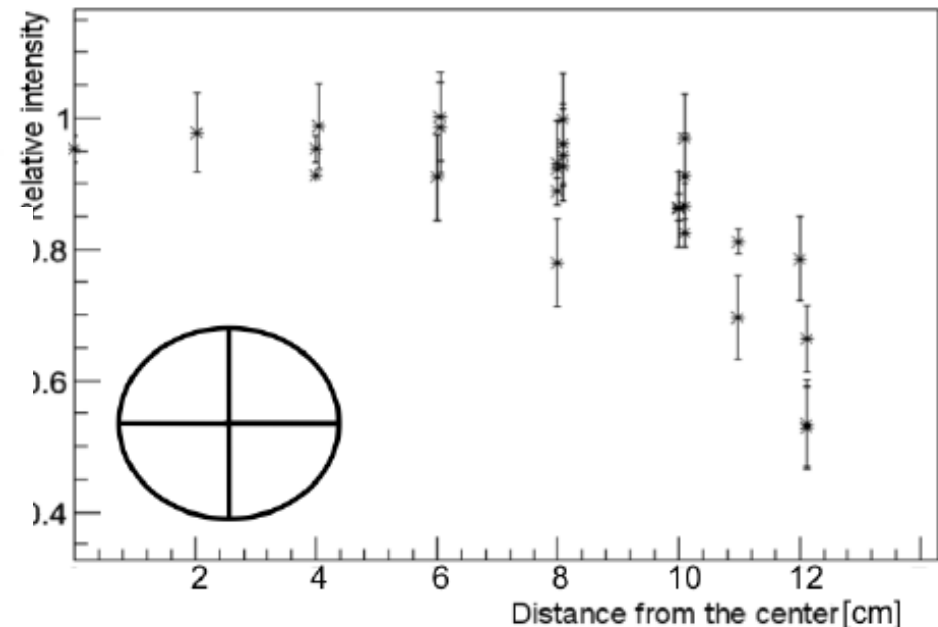
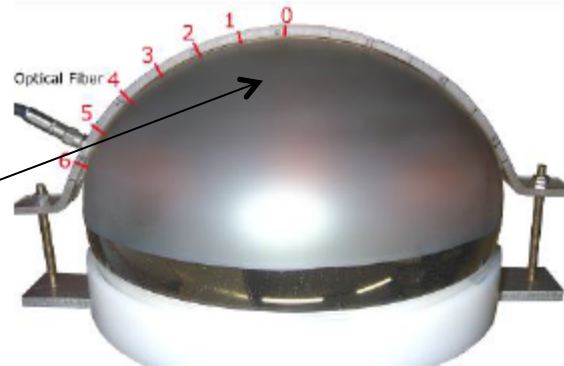
*Gain for different PMT models*

# Results on PMT characterization



Response uniformity for Hamamatsu R5912 PMTs

Distances on PMT surface

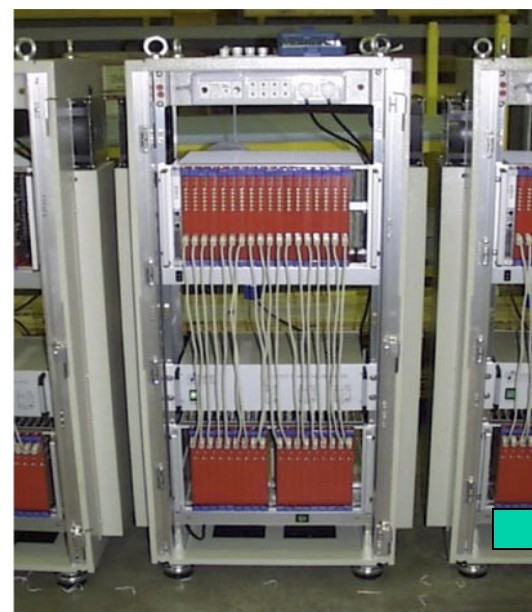


# The need for an upgraded electronics

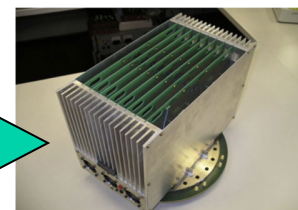
- Architecture of ICARUS-T600 electronics is based on analogue low noise “warm” front-end amplifier, a multiplexed 10-bit 2.5 MHz AD converter and a digital VME module for local storage, data compression & trigger information.
- A signal to noise ratio better than 10 and a  $\sim 0.7$  mm single point resolution were obtained during the LNGS run, resulting in precise spatial reconstruction of events and allowing to measure muon momentum by multiple scattering (MS) with  $\Delta p/p \sim 16\%$  in the 0.4-4 GeV/c range.
- Even though well suited for larger size LAr-TPC, ICARUS-T600 electronics is affected by some limitations, like the asynchronous sampling of all channels within 400 ns sampling time, which slightly affects the MS measurement, and data throughput mainly due to the choice of VME standard (8-10 MB/s).
- Some conceivable improvements concern:
  - adoption of high frequency serial ADCs with synchronous sampling;
  - housing and integration of electronics onto detector;
  - adoption of a modern serial bus architecture with optical links for faster transmission rate (Gbit/s).
- A cold front-end option, with warm digital processing, is being investigated. Prototypes, developed in collaboration with BNL, will be tested at CERN.

# New simplified/compact design

- A relevant change concerns the adoption of serial ADCs (10-12 bits, one per channel) in place of the multiplexed ones used in T600 al LNGS.
- The main advantage is the *synchronous* sampling of all channels (at 400 ns sampling time) of the whole detector, relevant for instance to the improvement of the muon momentum measurement by MS.
- The digital part is fully contained in a single high performance FPGA per board, that handles signal filtering and organizes the information provided by the serial ADCs.
- A new, compact design, has been conceived to host both analogue and digital electronics directly on the ad-hoc flanges (512 channels).
- Prototype boards are under test at INFN-LNL.



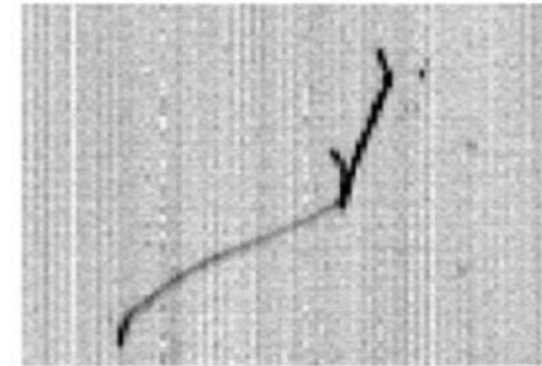
*From 595  
to 10 liters*



# The induction/collection signals

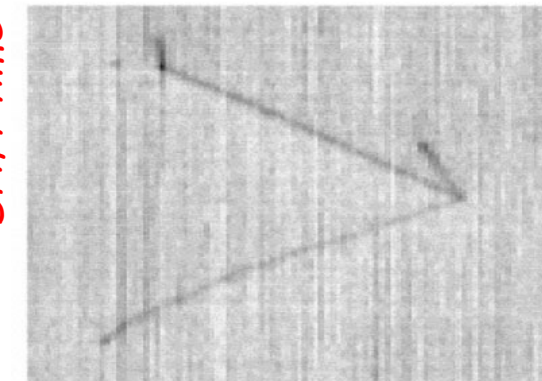
- In ICARUS-T600 "charge mode" front-end on induction2 view ("analog" integration on the bipolar signal) was chosen to recover charge information from the induction signal area as in collection, avoiding additional quantization errors.
- Induction2 front-end still requires further optimization, addressing mainly:
  - the signal pulse height, affected by the preamp rise-time ( $\sim 2 \mu\text{s}$  peaking time);
  - the residual undershoot of the electronic chain, degrading the reconstruction in particular of complex event topologies in presence of large energy deposition.
- Improvement of induction1 view signals are also being investigated.

Collection

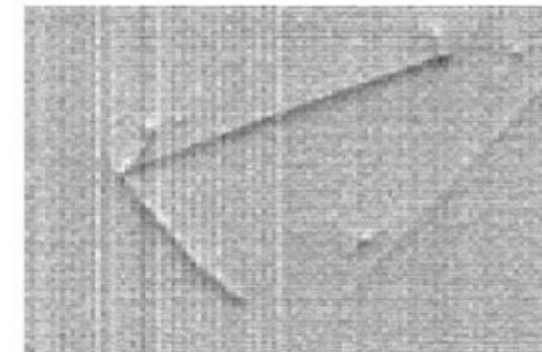


Induction-2

Drift time



Induction-1



Wires



***Thank you!***